

Fabrication and Characterization of Advanced Triple-junction Amorphous Silicon Based Solar Cells

PHASE I – Quarter 3

Quarterly Technical Progress Report

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Section 1

Executive Summary

This quarterly technical progress report covers the highlights of the research activities and results on the project of “The Fabrication and Characterization of High-efficiency Triple-junction a-Si Based Solar Cells” at the University of Toledo for the Period of September 1, 2005 to November 30, 2005, under NREL TFPPP subcontract number ZXL-5-44205-06.

Following this Executive Summary are three sections describing research performed during this quarter related to the tasks under this subcontract. The major technical progresses of these sections are summarized as follows:

Section 2: DC Bias Effect on Nanocrystalline Silicon Solar Cell under a High Power High Pressure Regime

We present the effect of applying DC external bias voltage to the substrate during preparation of a nanocrystalline silicon solar cell. The deposition rate, grain size, orientation property is found to be independent of the bias conditions, whereas the crystal volume fraction shows drastic change by varying bias value. This modification results in cell performance variations. A positive bias of 20 V exhibits the highest efficiency of 7.7%, while further positive bias and any negative bias produces lower efficiencies than the one made at zero bias (~6.0%). Even if we adjust the crystal volume fraction so as to obtain 50% which is done by changing hydrogen dilution ratio for several bias condition, a bias of +20V leads to the maximum efficiency, suggesting that the appropriate positive bias value (~+20 V) is effective in improving nc-Si:H solar cell performances.

Section 3: Effects of hydrogen dilution grading in active layer on performance of nanocrystalline single junction bottom component cell and corresponding a-Si:H based triple junction solar cells

The effect of hydrogen dilution grading on preparation of nanocrystalline silicon (nc-Si:H) intrinsic layer has been studied in the present work. Using hydrogen dilution grading, nc-Si:H single junction solar cells have been fabricated at a high deposition rate 8 Å/s with considerable high spectral response in longer wavelengths. The same grading in R has lead to different structural properties at the p/i interface with the present choices of final values of R. A requirement of proper coupling of grading with thickness is evident from the present study. Triple junction a-Si/a-SiGe:H/nc-Si:H cells have been fabricated using the nc-Si:H single junctions in the present study and a conversion efficiency of 11.2% is achieved. The J_{sc} of triple junction cells are shown to be limited by that of the nc-Si:H bottom components and remarkable improvement in FF is noticed in triple junction cells compared to the same in the corresponding nc-Si:H single junctions. Using spectroscopic ellipsometry, evaluation of crystalline volume fraction at different level of growth is undergoing, which will enable fine-tuning of grading in hydrogen dilution to tackle p/i interface properties and related results will also be discussed.

Section 4: Fabrication of a-SiGe:H Bottom Cells by VHF-PECVD with High Deposition Rate

Using Very-high-frequency (VHF) PECVD technique with a frequency of 70 MHz, device-quality a-SiGe i-layers were prepared by using gas source of Si_2H_6 and GeH_4 mixture at a high deposition rate of ~ 10 Å/sec. Film uniformity was studied with different processing pressures, which revealed that relative good homogeneous films on a $10 \times 10 \text{ cm}^2$ sample was preferred to be grown at low pressure (~ 0.45 Torr). Si/Ge ratio and hydrogen dilution are two main factors for the optimization on a-SiGe:H i-layer quality. Incorporating the optimum a-SiGe i-layer, an initial active-area (0.25 cm^2) cell efficiency of 8.6% ($V_{oc}=0.612 \text{ V}$, $J_{sc}=21.64 \text{ mA/cm}^2$, $FF=0.65$) has been achieved in narrow bandgap a-SiGe:H n-i-p single-junction structure. The efficiency is reduced by 13% after 100 hours of light soaking.

Section 2

DC Bias Effect on Nanocrystalline Silicon Solar Cell under a High Power High Pressure Regime

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Abstract

We present the effect of applying DC external bias voltage to the substrate during preparation of a nanocrystalline silicon solar cell. The deposition rate, grain size, orientation property is independent of the bias conditions, whereas the crystal volume fraction shows drastic change by varying bias value. This modification results in cell performance variations. A positive bias of 20 V exhibits the highest efficiency of 7.7%, while further positive bias and any negative bias produces lower efficiencies than the one made at zero bias (~6.0%). Even if we adjust the crystal volume fraction so as to obtain 50% which is done by changing hydrogen dilution ratio for several bias condition, +20V shows the maximum efficiency, suggesting that the appropriate positive bias value (~+20 V) is effective in improving nc-Si:H solar cell performances.

Motivation

Hydrogenated nanocrystalline silicon (nc-Si:H) solar cells are one of the most attractive candidates for the bottom component of an amorphous silicon (a-Si:H) based multi-junction solar cell such as tandem and triple-junction solar cells due to its stability and preferable bandgap energy as a bottom component. Furthermore, high spectral response at long-wavelength region (> 600 nm) of incident sun-light to which nc-Si:H bottom component mainly contributes, is essential in improvement of MJ solar cell performance. The nc-Si:H solar cell, however, suffers from a low absorption coefficient in the red portion of the visible sunlight spectrum, and requires only a few micron thickness to be effective, indicating that this technique of high-rate deposition with high quality material is indispensable. Several authors have reported on high deposition rate nc-Si:H films and of solar cells using high power, high pressure regimes [1-3], and their cell efficiencies reached up to 10.3% with an 11 \AA/s deposition rate [3]. In order to improve film quality, better techniques to produce high quality nc-Si:H films are required.

A high power, high pressure regime provides low positive ion flux and energy due to the reduction of the electron temperature in the discharge, thus recognizing that less ion bombardment than conventional low powers low pressure regimes will be required. Very high frequency (VHF) technology also allows us to moderate ion bombardment as well and therefore produce high quality nc-Si:H films with high rate deposition.[2,3] In this study, an external DC bias voltage application is introduced as another technique to moderate ion bombardment in the deposition regime of high power, high pressure. Appropriate ion bombardment is helpful for realizing ordered a-Si:H network and profitable towards nc-Si:H film deposition

[4,5], so that the ion energy moderation through external DC biasing to the substrate in the discharge has an effect on the quality of nc-Si:H film.

Experimental detail

The capacitively-coupled parallel-plate (CCP) type RF(13.56 MHz) - plasma enhanced chemical vapor deposition (PECVD) system produces nc-Si:H films under a high power, high pressure regime which creates a high deposition rate with good material quality as mentioned above. Figure 1 shows the schematic diagram of utilized system in this study. The RF-powered electrode system has a 3 × 3 inch area, shower-head configuration, and is mounted with 1.5 cm electrode gap. The substrate is placed in the stainless steel holder which is mounted to the heater through ceramic parts, and also is connected by a wire, allowing the application of external DC voltage bias to the substrate (V_b). In this study, we apply $V_b = -60$ V to +60 V and examine the effect of V_b on nc-Si:H film deposition and cell performance.

Process gas mixtures of Si_2H_6 and H_2 ($R = [\text{H}_2] / [\text{Si}_2\text{H}_6]$) are introduced in this chamber after passing through a purifier. The substrate temperature was 300°C and the background pressure prior to deposition is always below 10^{-7} mbar. Each nc-Si:H film has 1.7 μm thickness. The standard conditions which were optimized under a given electrode gap (1.5 cm) are $R = 66$, pressure = 10.6 hPa, and a plasma power density = 1.0 W/cm³.

Our deposition apparatus has a multi-chamber system that is connected through a load-lock chamber, therefore doped layers in this study are deposited in the separate chambers without breaking the vacuum which are conventional CCP-type RF-PECVD using gas mixtures of SiH_4 and H_2 , and PH_3 or BF_3 dopant gas for a-Si:H n-layer and a-Si:H p-layer, respectively. nc-Si:H solar cell were fabricated on a stainless steel substrate that is covered with Ag and ZnO layer which is produced by ECD Ovonic Inc. (notated ECD-sub. in this study) on which n-i-p stacks with varying external DC bias values were applied during i-layer deposition, and an ITO front electrode. The cell area is 0.25 cm².

nc-Si:H films deposited on ECD-sub. allowed us to provide information on crystallinity such as crystal volume fraction deduced from Raman scattering spectroscopy with 488 nm Ar-laser excitation. The 488 nm laser can reach nc-Si:H i-layer through a-Si:H p-layer, since the p-layer has less than 20 nm thick. This indicates, however, that estimated crystal volume fraction exhibits slightly smaller value due to containing an amorphous phase volume of a-Si:H p-layer. The crystal volume fraction (X_c) is estimated by using $X_c = (I_{510} + I_{520}) / (I_{480} + I_{510} + I_{520})$, where I_{480} , I_{510} and I_{520} are the integrated intensities at 480, 510 and

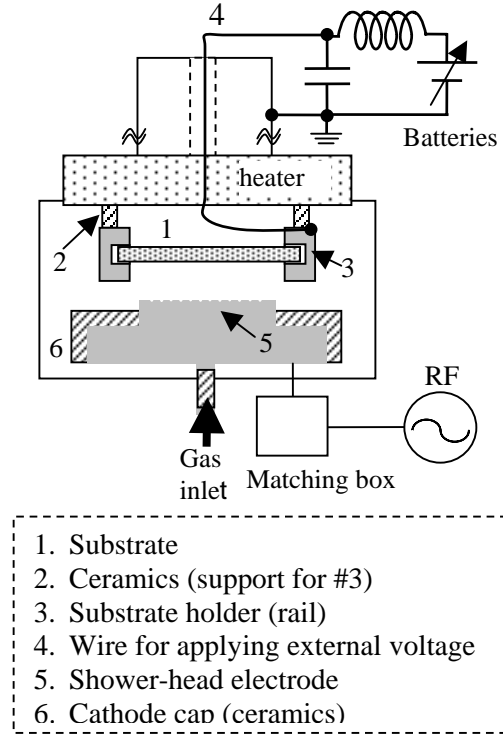


Fig.1 Schematic diagram of deposition chamber for nc-Si:H films.

520 cm^{-1} , respectively. X-ray diffraction (XRD) measurements revealed orientation properties as well as the grain size which is estimated by Scherer's formula.

Fabricated cells undergo I-V measurements with AM 1.5 illumination and external quantum efficiency (EQE). We estimate the film thickness of nc-Si:H layer from interference fringes of EQE spectrum, since ECD-sub. does not provide enough back reflector and provides clear interference fringes in long wavelength region more than 600 nm.

nc-Si deposition

First, the dependence of the deposition rate (r_d) and the crystal volume fraction (X_c) with respect to the external DC bias (V_b) will be discussed. The r_d is independent of V_b to the substrate and has almost a constant value of 9.4 \AA/s as shown in Fig. 2(a). In the deposition under the high power, high pressure regime, large amounts of neutral radicals such as SiH_3 reach the substrate surface quickly, and are deposited to make nc-Si:H films with high rate deposition. Ions (consisting mainly of positive ions) are assumed to be affected by the electric field effect due to the external DC bias to the substrate in this study. Additionally these ions will exist in the discharge, attach on the surface, and bombard the deposited surface. The ion flux, however, amounts to only less than 0.01% of the radical flux [6], therefore having no significant effect of DC bias on the deposition rate, especially in the high power, high pressure regime as shown in Fig. 2(a).

Figure 2(b) explains the effect of positive ion bombardment during nc-Si:H deposition. High positive ion energy produced by negative biasing, enhances nucleation in the nc-Si phase evolution, resulting in higher X_c as shown in Fig. 2(b), and after exceeding a certain threshold, the ion bombardment becomes detrimental to the nc-Si:H having high X_c due to it having a large positive ion energy. In contrast, the opposite polarization alleviates the ion energy, leading to less X_c due to the lower ion bombardment onto the deposited surface, thus suggesting that the low ion bombardment will result in less defect density in nc-Si:H film. Therefore, we expect a positive bias applied to the substrate produces a preferable nc-Si:H film. Note that when examined by XRD analysis, the DC biasing has no effect on the grain size (~ 10 nm), as well as the orientation property.

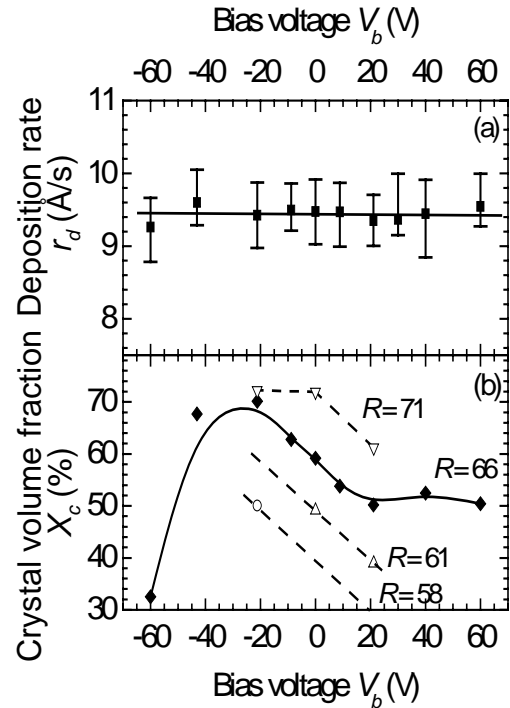


Fig. 2 Deposition rate (r_d) and crystal volume fraction (X_c) as a function of external DC bias to the substrate (V_b) in (a) and (b), respectively. Solid and dashed lines in (a) and (b) are eye guides. In (b), the hydrogen dilution ratio R dependency is also indicated.

These results also suggest that the DC bias application act supplementarily on nc-Si:H deposition mechanism. The nucleation rate is governed by the given hydrogen dilution ratio R , since the other deposition condition is maintained, expect V_b value. If one applies external DC bias to the substrate, additional or moderate ion bombardment contributes to film deposition mechanism, mainly to nucleation rate and nc-Si phase evolution. However, precursors such as neutral radicals still prevail among the deposition mechanism as a whole, judging from the constant behavior of r_d . The behavior of high V_b range of which X_c does not vary at $V_b > +20$ V with no changing for the grain size and the orientation supports this speculation. We suppose that hydrogen dilution ratio R will mainly control the behavior of hydrogen impinging to the deposited surface contributing nucleation of nc-Si phase, eventually set a baseline of X_c . Further small adjustment of X_c is achievable by changing the V_b value due to control the ion energy as shown the results of dependence of X_c on R in Fig. 2 (b). It should be note that X_c tends to be saturated at around 70%. In estimation of X_c from Raman, the X_c does not exceed 80% [7], and amorphous phase can be overestimated due to the differences of optical absorption coefficient between a-Si:H phase and nc-Si:H phase for the excitation wavelength of Ar-laser, and of cross section of those phase etc. Moreover, estimated X_c in this study has a chance to decrease the X_c slightly compare to the one without a-Si:H top layer. Therefore, the obtained nc-Si:H film which has $X_c \sim 70\%$ might involve higher crystalline silicon volume than the calculated.

From these results, we assume that moderation of ion bombardment by DC voltage application to the substrate only will change the nucleation rate. More detailed analysis in growth direction will be required using spectroscopic ellipsometry and Raman scattering spectroscopy with different wavelength of excitation beam.

nc-Si cell performances

Figure 3 shows the cell performances at various bias voltages (V_b). As expected, positive bias exhibits higher J_{sc} and FF , eventually higher efficiency ($> 7\%$) than the ones made at zero bias ($\sim 6\%$) or at any negative bias. In addition, there exists an optimum positive bias voltage around +20 V, and further positive biasing is unfavorable, indicating that moderated ion energy could not effectively remove hydrogen impinging from the surface or the desorbed Si precursors which attached at undesirable sites to make profitable nc-Si:H films. It should be noted that an appropriate positive bias contribute mainly to J_{sc} and FF enhancement as show in Fig. 3. Figure 4 represents EQE spectra. It clearly explains that the J_{sc} improvement at around $V_b \sim +20$ V is attributed to the enhancement of response at the

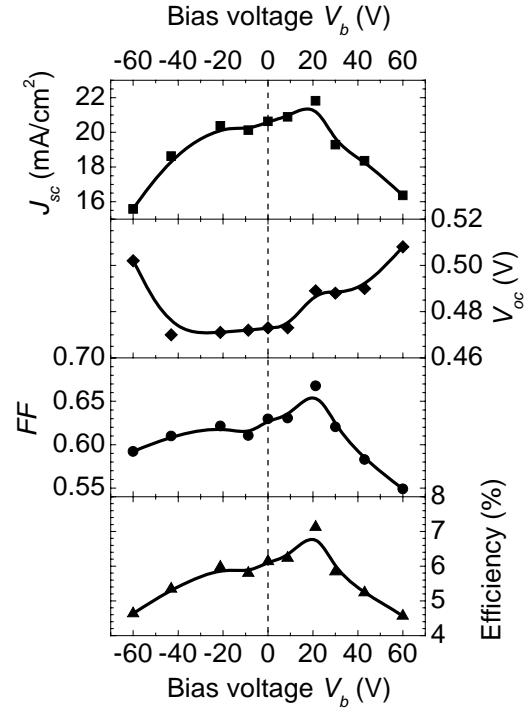


Fig. 3 Cell performances as a function of external DC bias to the substrate (V_b). Dashed line indicates the position of zero bias.

green-red light portion of the solar spectrum as shown in inset of Fig. 4, implying an appropriate positive bias can achieve preferable carrier transportation property than the one without bias and negative bias, and result in better bulk quality. Figure 4 also indicates the improvement of blue response by applying $V_b \sim +20$ V. The p-i interface will experience a lower ion energy deposition, but it requires more detailed analysis for the p-i interface evaluation.

Therefore it is suggested that better quality material can be deposited at $V_b \sim +20$ V judging from J_{sc} , FF and EQE behaviors. We also demonstrate the effect of hydrogen dilution ratio on $V_b = 0$ V, -20 V, and $+20$ V bias cases in order to vary the baseline of X_c as shown in Fig. 2(b).

Figure 5 exhibits the dependence of V_{oc} and FF on X_c as R was varied. The V_{oc} increases gradually with decreasing X_c regardless of V_b value, however FF as well as J_{sc} (but not shown in the figure) represents a maximum point at $X_c = 50 \sim 60\%$, especially in the $V_b = +20$ V. At $X_c = 50 \sim 60\%$, nc-Si:H cell tends to show higher performances⁴, and is sensitive over the i-layer quality. It is expected that moderated deposition by the basing technique can create relatively ordered a-Si:H tissue surrounding the nc-Si phase, and realize a better carrier transportation. These results convince that the appropriate positive bias and R value improves nc-Si:H film quality and its solar cell performances, although the positive bias as well as the R value exists at narrow process window.

We should also mention that the hydrogen dilution ratio and the appropriate bias condition depend strongly on the chamber geometry, electrode configuration, and plasma excitation frequency. Higher plasma excitation frequency than RF will also be helpful to further moderate ion energy as well as the flux, in addition to external DC bias voltage application. Therefore VHF with biasing technique should be offered to achieve further ion energy moderation.

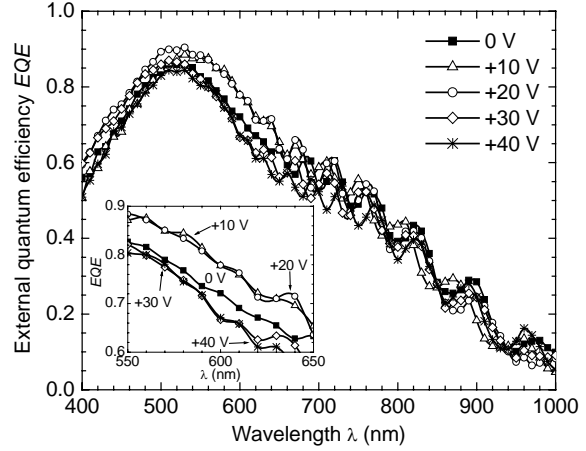


Fig. 4: External quantum efficiency spectra for various positive bias voltage cases. Inset spectra exhibit the responses at green-red light part (550 nm \sim 650 nm).

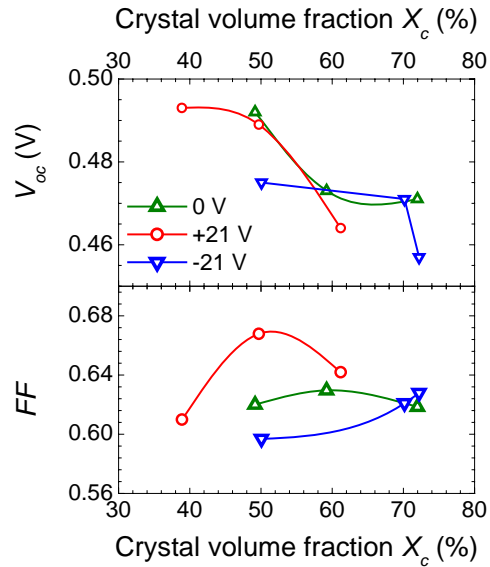


Fig. 5 Open circuit voltage (V_{oc}) and fill factor (FF) as a function of crystal volume fraction at DC bias voltage V_b of 0 V, -20 V and $+20$ V.

Conclusions

The external DC bias has not effect on the deposition rate, whereas provides significant modification for the crystal volume fraction, eventually cell performances. The positive 20 V bias exhibits the highest n-i-p cell performances of 7.7% efficiency ($J_{sc} = 22.4 \text{ mA/cm}^2$, $V_{oc} = 0.5 \text{ V}$, $FF = 0.685$) so far, without optimized a back reflector. We suggest that external DC biasing is useful technique to improve the nc-Si:H film quality and its solar cell performances.

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Section 3

Effects of hydrogen dilution grading in active layer on performance of nanocrystalline single junction bottom component and corresponding a-Si:H based triple junction solar cells

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ABSTRACT

Using hydrogen dilution grading in nanocrystalline silicon (nc-Si:H) intrinsic layer, considerably high spectral response has been achieved in the longer wavelength (650nm-1000nm) of solar spectrum from single junction solar cells, to be used as bottom junction in monolithic triple junction a-Si:H based thin film solar cells. The intrinsic layers have been deposited with a high deposition rate of 8 Å/s, using VHF PECVD deposition technique from Si₂H₆ diluted with H₂. In the present work, using R ($R=[H_2]/[Si_2H_6]$) from an initial value 50 to different final values viz. 40, 37.5 and 35, single junction nc-Si:H cells have been fabricated and the same single junction components have been applied as bottom junction to fabricate a-Si:H/a-SiGe:H/nc-Si:H triple junction structure where the properties of top and middle junctions were kept fixed. The short circuit current of the triple junction cells is shown to be limited by the bottom junction and the fill factor has been improved in triple junction cells compared to the same obtained from the corresponding single junction cells used as nc-Si:H bottom junction. Comparison of the fill factors under red (>630nm) illumination and that under blue (<510nm) illumination for these single junction nc-Si:H cells indicated structural quality of p/i interface and bulk of the i-layer of nc-Si:H solar cells. A conversion efficiency of 11.2% has been achieved from triple junction solar cell. The light induced degradation studies are currently in process for triple junction cells under a 100 mW/cm² white light illumination. Using spectroscopic ellipsometry, evaluation of crystalline volume fraction at different level of growth is undergoing, which will enable fine-tuning of grading in hydrogen dilution.

INTRODUCTION

Hydrogenated nanocrystalline silicon (nc-Si:H) material has received enormous attention as intrinsic thin film layer either in single junction or in bottom component of a multijunction a-Si:H based solar cells [1]. This importance owes to its enhanced response in longer wavelength (>650nm) of solar spectrum and higher light induced stability over a-Si:H and a-Si:Ge:H materials. Maintaining a proper ratio of crystalline and amorphous phase in silicon film is an essential and critical requirement to fabricate high efficiency solar cells [2]. Variation of the hydrogen dilution flow ratio in the Si-containing feed gas is a conceptually simple and thus widely-practiced method for controlling the phase composition in nc-Si:H films. Due to lower absorption co-efficient of nc-Si:H materials, a considerably thick (>1μm) layer is needed for sufficient absorption of photons. If the hydrogen dilution ratio is kept constant during deposition, the crystalline volume fraction increases with thickness due to a well-recognized evolutionary pattern of

mixed-phase Si:H film growth [3]. To suppress the natural structural evolution of nc-Si:H with thickness, decreasing hydrogen dilution grading has been recommended so that a constant, but adjustable crystalline volume fraction can be obtained throughout the growth process.

Application of hydrogen dilution grading and its consequences on solar cells performance are not yet understood properly. In the present work, choice of a grading and its effects on the properties of nc-Si:H single junction and corresponding triple junction solar cells using nc-Si:H bottom component have been discussed.

EXPERIMENTAL

The silicon thin films have been deposited by plasma enhanced chemical vapor deposition (PECVD) technique using either RF (13.56 MHz) or VHF (70 MHz) for different intrinsic and extrinsic layers. The properties of top (a-Si:H) and middle (a-SiGe:H) components of triple junction structure have been kept fixed during this study while the single junction properties have been varied in bottom (nc-Si:H) component. The device structure of the single junction solar cell is stainless steel/Ag/ZnO/n-i(nc-Si:H)-p/ITO and for the triple junction, stainless steel/Ag/ZnO/n-i(nc-Si:H)-p/p⁺/n⁻/n-i(a-SiGe:H)-p/p⁺/n⁻/n-i(a-Si:H)-p/ITO. Thin and flexible 10 cm x 10 cm stainless steel, coated with thin layers of Ag and ZnO has been used as substrates for device fabrication, the area of individual devices being 0.25 cm² as defined by area of the transparent conducting top contact layer. The metal and transparent conducting metal oxide layers have been deposited using RF sputtering technique. The deposition conditions of n-type and p-type layers have been kept unaltered for the variation of i-layer properties in single junction nc-Si:H solar cells. The intrinsic nc-Si:H layers have been deposited using VHF PECVD with a power density 0.7 Watt/cm² from Si₂H₆ diluted with H₂. The substrate temperature and chamber pressure for the deposition of i-layer have been fixed at 400°C and 0.25 Torr respectively. The hydrogen dilution has been defined as $R=[H_2]/[Si_2H_6]$ and has been varied with deposition time to achieve dilution grading from a higher initial R to a lower final R. In the present study R has been varied from an initial value of 50 to a series of different final values (corresponding deposition time in parenthesis): sample A: 40 (20 minutes), sample B: 37.5 (25 minutes) and sample C: 35 (30 minutes), to deposit the nc-Si:H layers in single junction bottom component solar cells. The effect of these variations has been studied for single as well as triple junction cells.

The fabricated solar cells have been characterized with current-voltage (I-V) characteristic measurement using AM1.5G illumination from a solar simulator. The open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), fill factor (FF) and conversion efficiency (η) have been evaluated from this measurement. The same measurement has also been done under optical filters short pass <510 nm and high pass >630 nm to evaluate FF under blue (FF_b) and red (FF_r) illumination respectively. The spectral response of the solar cells has been evaluated using quantum efficiency calculation in the range of 350 nm -1000 nm. To monitor light induced effect in performance of solar cells, a white light illumination of 100 mW/cm² has been used and solar cells have been light soaked at room temperature for durations of several (100-1000) hours.

RESULTS and DISCUSSIONS

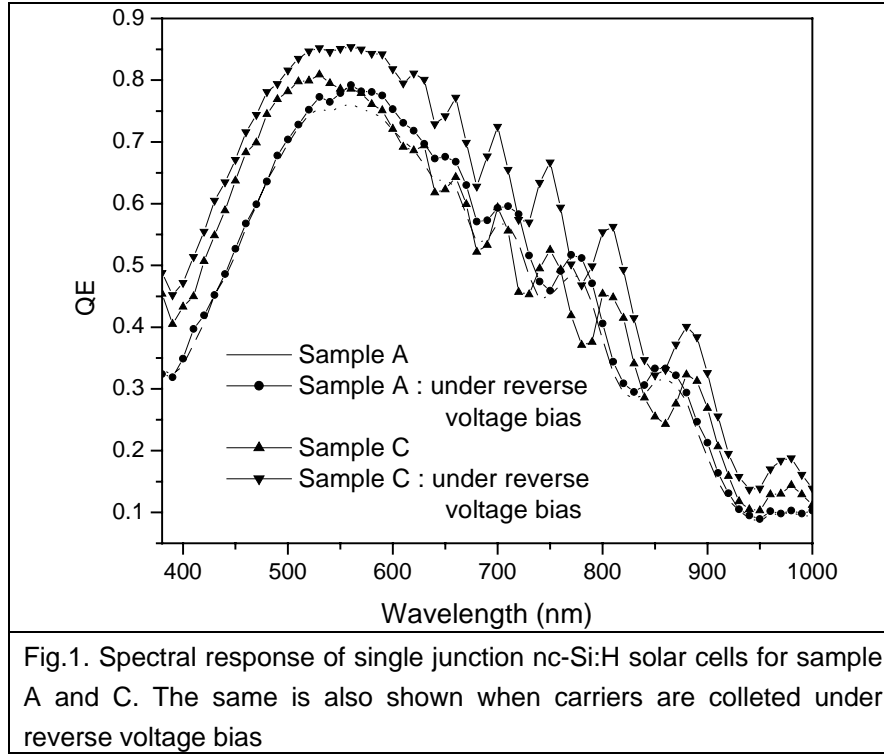
Results of single junction nc-Si:H cells

In this present study, for the samples A, B and C, the initial value of R is the same, 50. Therefore, the variation in solar cell properties is mainly governed by the choice of final value of R. Though the deposition time for A, B and C are different, the grading (rate of change in R) is chosen to be almost the same by proper choice of final value of R. The parameters from I-V characteristics of single junction nc-Si:H cells have been shown in Table 1. The J_{sc} is increased with the increase in deposition time from sample A to sample C due to higher absorption of photons. The FF is found to be gradually decreased, while V_{oc} remains unchanged under this variation. In Table 2, a comparison of FF measured under different spectrum distribution shown for these samples. The FF_b and FF_r decrease alongwith the decrease of FF, however, in case of sample A, $FF_b > FF_r$, while in case of samples B and C, FF_b seems to fall faster than FF_r , reaching a condition $FF_b < FF_r$. Since, FF_b is a measure of carrier collection capability at p/i interface, this observation indicates a deterioration of interface quality from sample A to sample C. Whereas, since FF_r refers to the carrier collection from the bulk, the deterioration of bulk property is less significant as that of the p/i interface.

Table 1. I-V parameters of single junction nc-Si:H solar cells deposited with graded R				
Sample	V_{oc} (V)	J_{sc} (mA/cm ²)	FF (%)	(%)
A	0.411	20.83	65.6	5.6
B	0.405	21.26	63.0	5.4
C	0.410	21.51	61.2	5.4

Table 2. Fill factors of sample A, B and C under white, FF (AM1.5G); blue, FF_b (<510nm); and red, FF_r (>630nm) illuminations			
Sample	FF (%)	FF_b (%)	FF_r (%)
A	65.6	65.7	64.7
B	63.0	63.1	63.4
C	61.2	61.5	62.0

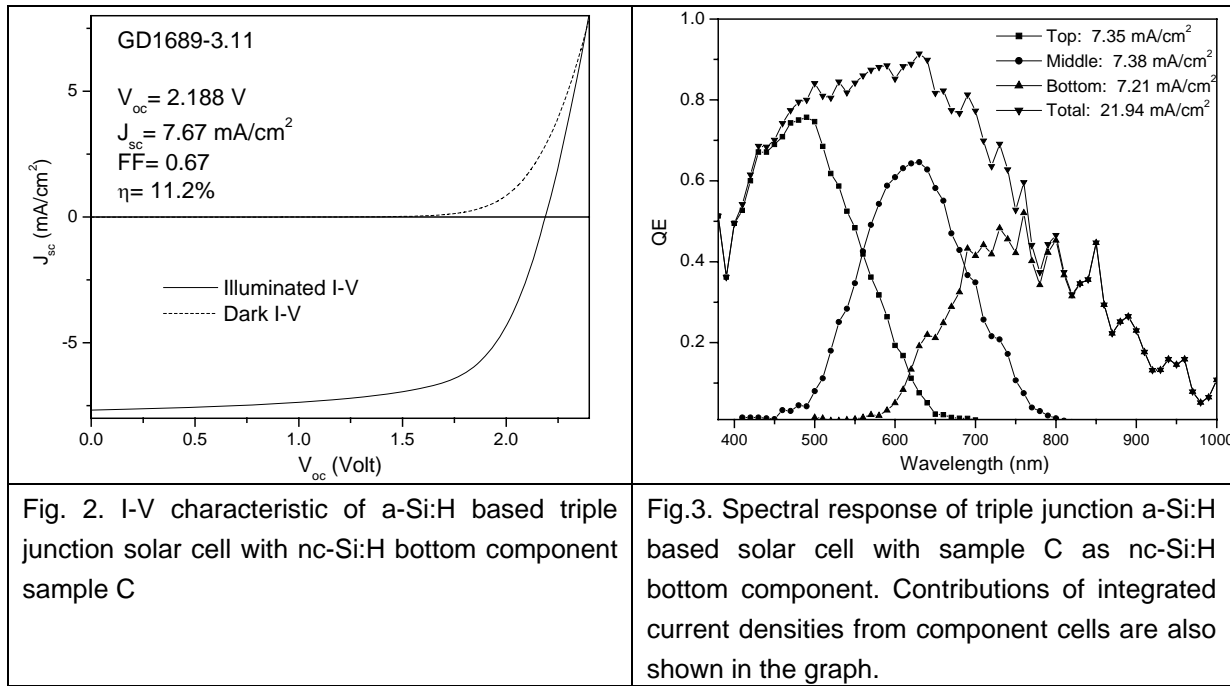
The QE curves for the samples A and C are shown in Fig. 1. A reverse voltage bias has been used for better carrier collection during QE measurement and are also shown for comparison between the samples A and C. A high spectral response has been obtained from both the samples A and C, while the response increases further under reverse voltage biased collection. It is interesting to note that, the QE under reverse voltage bias, does not improve in the wavelength range <500 nm for sample A, whereas there is a considerable increase for the sample C. This also confirms the deterioration of p/i interface properties, as an effect of the final value of R. Therefore, the same grading in R could lead to different structural properties at the p/i interface due to improper choice of final value of R and the corresponding deposition time. Thus, to increase current from a hydrogen dilution graded intrinsic layer maintaining same bulk and interface qualities, the thickness increase should be coupled with proper grading.



Results of triple junction a-Si:H based solar cells

Triple junction solar cells have been fabricated using samples A, B and C as the bottom components. The I-V parameters are shown in the Table 3. The I-V characteristics of a triple junction solar cell with sample C as the bottom component, is shown in Fig. 2 and the QE curves of the same is shown in Fig. 3. It is evident from Fig. 3, that the J_{sc} of the triple junction cell is limited by that of the bottom component. Considering Table 1 and Table 3, the J_{sc} increases in triple junction cells corresponding to the increase in J_{sc} in the nc-Si:H bottom component. A remarkable improvement in FF is achieved in triple junction cell compared to that of the corresponding single junction components. However, trend of drop in FF is also present in the triple junction cells from the sample with A to with C. As shown in Fig. 3, the utilization of longer wavelength part of solar spectrum is achieved through the fabricated triple junction solar cells in the present work.

Table 3. I-V parameters of triple junction a-Si:H based solar cells with nc-Si:H bottom components A, B and C				
Triple jn.Sample	V_{oc} (V)	J_{sc} (mA/cm ²)	FF (%)	η (%)
With A	2.160	6.92	72.1	10.7
With B	2.164	7.17	71.1	11.0
With C	2.188	7.67	67.0	11.2



CONCLUSIONS

Using hydrogen dilution grading, nc-Si:H single junction solar cells have been fabricated at a high deposition rate 8 Å/s with considerable high spectral response in longer wavelengths. The same grading in R has led to different structural properties at the p/i interface with the present choices of final values of R. A requirement of proper coupling of grading with thickness is evident from the present study. Triple junction a-Si/a-SiGe:H/nc-Si:H cells have been fabricated using the nc-Si:H single junctions in the present study and a conversion efficiency of 11.2% is achieved. The J_{sc} of triple junction cells are shown to be limited by that of the nc-Si:H bottom components and remarkable improvement in FF is noticed in triple junction cells compared to the same in the corresponding nc-Si:H single junctions. Measurement of light induced effects is in process and will be reported in the meeting. Using spectroscopic ellipsometry, evaluation of crystalline volume fraction at different level of growth is undergoing, which will enable fine-tuning of grading in hydrogen dilution to tackle p/i interface properties and related results will also be discussed.

ACKNOWLEDGEMENT

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Section 4

Fabrication of a-SiGe:H Bottom Cells by VHF-PECVD with High Deposition Rate

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Abstract

Using Very-high-frequency (VHF) PECVD technique with a frequency of 70 MHz, device-quality a-SiGe i-layers were prepared by using gas source of Si_2H_6 and GeH_4 mixture at a high deposition rate of ~ 10 Å/sec. Film uniformity was studied with different processing pressures, which revealed that relative good homogeneous films on a $10 \times 10 \text{ cm}^2$ sample was preferred to be grown at low pressure (~ 0.45 Torr). Si/Ge ratio and hydrogen dilution are two main factors for the optimization on a-SiGe:H i-layer quality. Incorporating the optimum a-SiGe i-layer, an initial active-area (0.25 cm^2) cell efficiency of 8.6% ($V_{oc}=0.612 \text{ V}$, $J_{sc}=21.64 \text{ mA/cm}^2$, $FF=0.65$) has been achieved in narrow bandgap a-SiGe:H n-i-p single-junction structure.

Experimental

Using the VHF-PECVD technique with a frequency of 70 MHz in our UT multi-chamber load-locked deposition system, the narrow bandgap a-SiGe:H i-layers were prepared at high deposition rates of ~ 10 Å/s under the deposition pressure in the region of 0.2-0.6 Torr. T_s is 400°C . The gas flow ratio of $[\text{H}_2]/([\text{Si}_2\text{H}_6]+[\text{GeH}_4])$ was graded during the i-layer deposition. Film thickness was derived from interference fringes on reflectance spectrum measured for samples made on $4'' \times 4''$ stainless steel substrate. The doped layers and the buffer layers for narrow bandgap a-SiGe:H n-i-p single-junction structure were made using standard RF-PECVD technique with deposition rates of 1-2 Å/s. The fluctuation of I-V parameters is mainly along the gas flow direction from the gas inlet area to the gas outlet area, so the uniformity is defined as solar cell I-V parameters and film deposition rates as functions of cell position counted from sample upstream side edge.

Results and Discussion

The a-SiGe film deposition rate (r_d) increases with the VHF-power before reaching the gas depletion region. r_d measured at the center of samples were 10 Å/sec, 9 Å/sec and 8.5 Å/sec corresponding to the power density of 40 mW/cm^2 , 20 mW/cm^2 and 13 mW/cm^2 , respectively, as seen in Figure 1. When the power density is 40 mW/cm^2 , the film close to the gas inlet has a higher deposition rate than most of the rest area. Uniform in terms of film's thickness is better at a lower power condition.

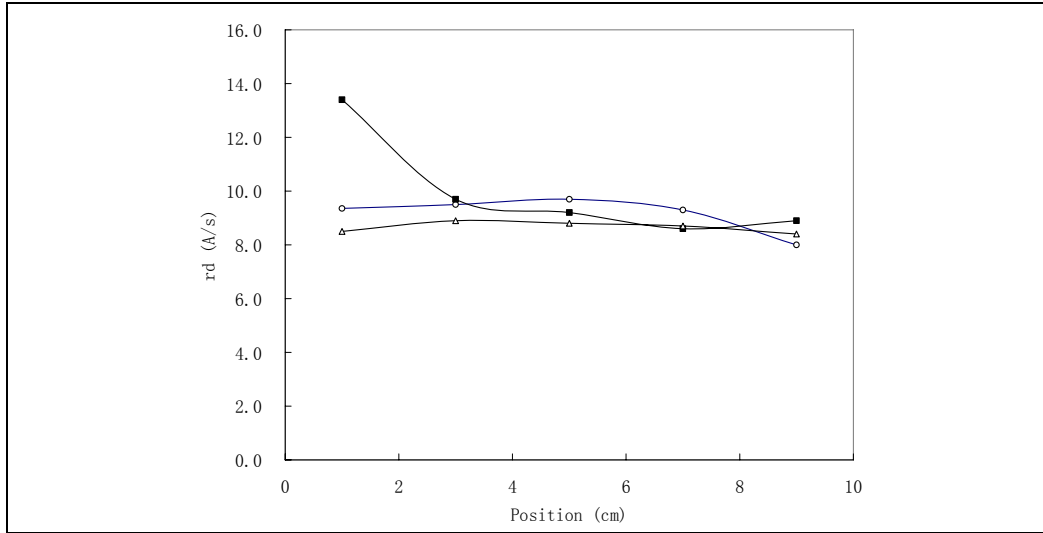


Figure 1 Deposition rates along the gas flow direction from the gas inlet to the outlet on 4" x4" samples. a-SiGe:H i-layers were made under 0.45 Torr with different VHF-power densities of 40 mW/cm² (square), 20 mW/cm² (circle) and 13 mW/cm² (triangle).

Figure 2 shows the solar cell I-V parameters distribution corresponding to different deposition pressure: 0.3 Torr, 0.45 Torr and 0.6 Torr. At 0.6 Torr, the V_{oc} and J_{sc} of center cells are lower than those at both edges. At 0.3 Torr, the center area cells have the largest V_{oc} among all cells. The V_{oc} distribution is relatively flat for sample made at 0.45 Torr. These samples are about 270 nm thick with variation less than 20 nm, so the influence of the i-layer thickness on V_{oc} is small. The V_{oc} change must be related to bandgap variations in the i-layer. It can imply that Si_2H_6 and GeH_4 dissociation rates are different along the gas flow direction under different pressure. Under 0.45 Torr, Si/Ge ratio in the film is higher at the gas inlet area than the down stream side, so the bandgap of the material near the gas outlet area is low. This is why J_{sc} is increased along the gas flow as seen in Figure 2. "U"-shape V_{oc} distribution under 0.6 Torr is not only related to the gas flow dissociation rates, but also to the Si_2H_6 and GeH_4 gas concentration. It is believed that GeH_4 amount is less at the down stream side, a large Si/Ge ratio in the film increases the V_{oc} . V_{oc} distribution under

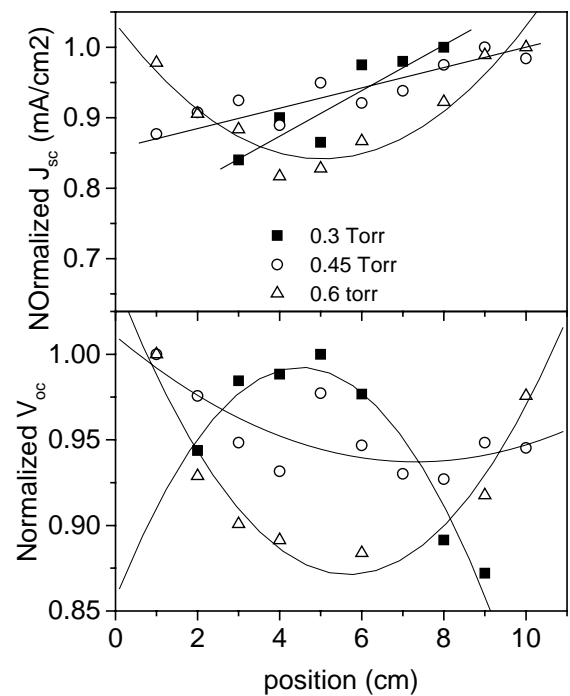


Figure 2 Distribution of V_{oc} and J_{sc} of VHF-PECVD a-SiGe:H solar cells along the gas flow. FF has a similar trend to V_{oc} and is not shown here. The lines are only guiding the eyes, which is the same for the following plots.

condition of 0.3 Torr depends mainly on the gas reaction rate at different area under the assumption of homogeneous gas concentration in the chamber in case of low deposition rate.

Figure 3 shows the I-V parameters of solar cells made with the above mentioned power density settings. The trend lines in top 2 figures are only guiding the eyes. First it can be seen from the V_{oc} and J_{sc} plots that lower power density leads to a uniform V_{oc} distribution and higher J_{sc} . Second the J_{sc} trend is opposite to the V_{oc} trend along the gas flow direction for each sample. J_{sc} drops with increasing V_{oc} and vice versa. This proves that the a-SiGe:H bandgap is changed along the gas flow direction, in other words Si/Ge ratio in the film changes.

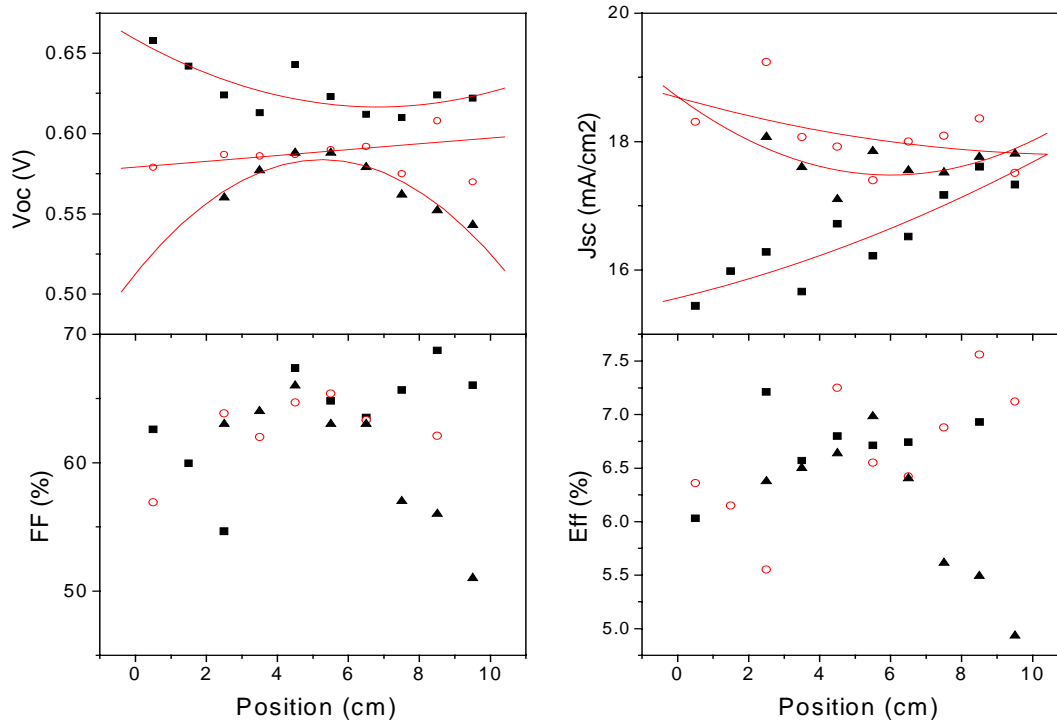


Fig. 3. I-V parameters of a-SiGe solar cells made at 0.45 Torr for different power density, which are 40 mW/cm² (triangle), 20 mW/cm² (square) and 13 mW/cm² (circle).

Under high deposition rate micro-voids tend to form and deteriorate the film quality because of the low radical surface mobility. Therefore, the deposition rate was controlled at around 10 Å/sec by using very high hydrogen dilution ratio R with values in the range of 50-90 and a low power density of 20 mW/cm². R value is defined as $[H_2]/([Si_2H_6]+[GeH_4])$.

An initial active-area (0.25 cm²) efficiency of 8.6% (V_{oc} =0.612 V, J_{sc} =21.64 mA/cm², FF=0.65) was achieved for an representative narrow bandgap a-SiGe:H n-i-p single-junction structure made at 0.45 Torr with a deposition rate of 10 Å/sec. Figure 7 displays the I-V curve and Figure 8 the QE graph. The integrated current on the QE graph are 20.20 mA/cm² and 19.18 mA/cm² for before and after 100 hours

of light soaking respectively. The main degradation is on FF, as seen in table 1. The degradation on efficiency is about 12.8%.

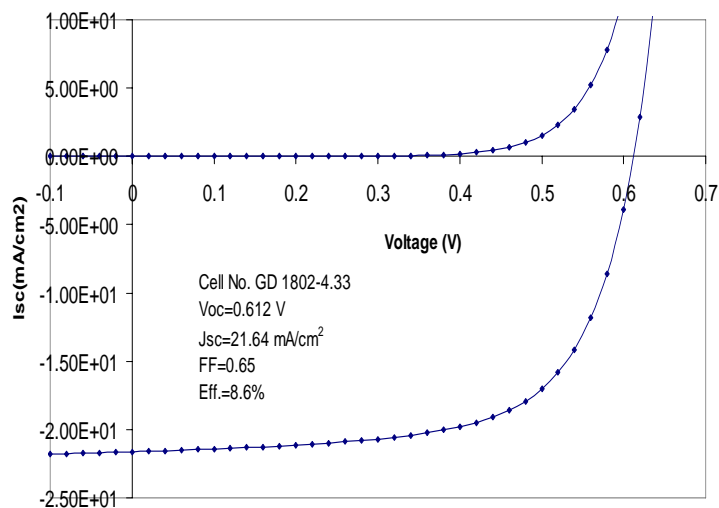


Figure 4 I-V curves of VHF-PECVD a-SiGe:H solar cell at high deposition rate of 10 Å/sec

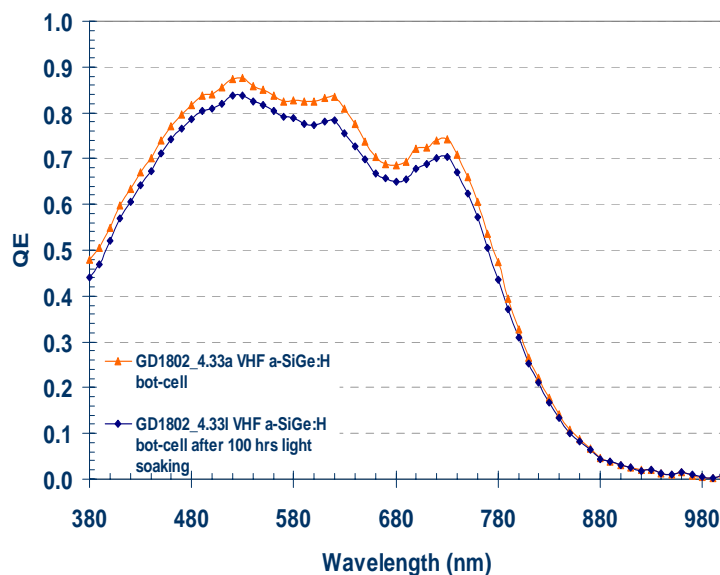


Figure 5 Quantum efficiency of a-SiGe cell before and after light soaking for 100 hours.

Table 1 Light induced degradation for a-SiGe bottom cell after 100 hours of light soaking

	V_{oc}	J_{sc}	FF	Eff
	(V)	(mA/cm ²)		(%)
Initial values	0.612	21.6	0.65	8.6
After 100 hrs of light soaking	0.593	20.7	0.61	7.5
Degradation (%)	3.1	4.4	6.1	12.8

Conclusions

Low pressure is preferable to obtain uniform film with a certain power density in the current chamber, where the gas enters the chamber from one side of the chamber wall. Gas reaction rate is different in the cathode area, but through optimizing the gas flow rate and power density under low pressure, especially the profiled hydrogen dilution, uniform a-SiGe:H cells of $10 \times 10 \text{ cm}^2$ are obtained at a deposition rate of 10 Å/sec . An representative initial efficiency of 8.6% has been obtained for narrow bandgap a-SiGe:H n-i-p single-junction structure made at 0.45 Torr with a deposition rate of 10 Å/sec . The efficiency is reduced by 13% after 100 hours of light soaking.